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DESIGN STUDY OF A FREE ELECTRON LASER STORAGE RING,(U)
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DESIGN STUDY OF A FREE ELECTRON LASER STORAGE RING *

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ABSTRACT

In this section the results of a design study for a free electron laser storage ring are discussed. The goal of the study was to show the feasibility of a storage ring beam to be used as the driver for a free electron laser. The requirements for such a storage ring in many respects are more demanding than the parameters of colliding beam storage rings; however, experience and results of many fundamental studies on existing storage rings give us confidence that none of the parameters required for a free electron laser storage ring exceeds the technical possibilities. In fact it was found that the storage ring parameters ~~as~~ described in this report are well within the state of the art and still leave significant freedom for further optimization.

Some of the most characteristic storage ring parameters as obtained in this design study are listed in ~~the following~~ a table.

SUMMARY OF STORAGE RING PARAMETERS

Energy	$E = 1$ GeV
Current total	$I = 1$ amp
per bunch	$i = 83$ mamp
number of bunches	$N_B = 12$
Circumference	$C = 258.56$ m
beam emittances	$\varepsilon_x = 3.6 \cdot 10^{-9}$ rad m
	$\varepsilon_y = 2.0 \cdot 10^{-9}$ rad m
energy spread - natural	$\sigma_e/E = 3.5 \cdot 10^{-4}$
- laser on	$\sigma_e/E = 4.0 \cdot 10^{-3}$
bunch length - natural	$\sigma_\ell = 11.5$ mm
- laser on	$\sigma_\ell = 130$ mm
total energy acceptance	$(\Delta E/E)_{max} = \pm 2.5\%$
rf-frequency	$f_{rf} = 111.3$ MHz
rf-voltage	$V_{rf} = 379$ kV
rf-power - to beam (laser off)	$P_B = 27$ kW
- cavity losses	$P_{cy} = 13$ kW
- total	$P_{tot} = 40$ kW
beam lifetime - laser on	$\tau_L = 10$ hours
- laser off	$\tau_0 = 34$ min

CONTENTS

I. DESIGN GOALS

In the previous sections the physics of the free electron laser system is described. It was found that the maximum laser power is strongly related to the maximum energy acceptance of the storage ring. This is due to the fact that every time the beam interacts with the laser the particle energy is modulated by the laser field. Although this modulation is coherent at the laser frequency, a feedback system to reduce this modulation is not feasible because the bending sections in the storage ring cause particles of different energies to travel along different paths which smear out the coherent energy modulation and leaves an incoherent increase of the energy spread in the beam. This blow up of the energy spread with time can be counteracted only by damping due to the energy dependence of the synchrotron radiation. The storage ring therefore has to be designed in such a way as to maximize the damping.

Other parameters like the beam size in the wiggler, the dispersion in the wiggler, etc., are the result of maximizing the energy transfer from the electron beam to the laser at a minimum blow up of the energy spread. Thus, the following boundary conditions for the design of the storage ring are assumed:

beam energy	$E = 1$ GeV
maximum energy acceptance of the ring	$\frac{\Delta E}{E} = \pm 2.5\%$
damping time for synchrotron oscillations	$n_{\varepsilon} < 1$ to 4×10^4 turns
beam emittance in the deflecting plane (vertical plane in our design) of the wiggler magnet	$\varepsilon_y = 2 \cdot 10^{-9}$ rad m
ratio of the beam sizes in the non-deflecting to deflecting plane of the wiggler magnet	$\frac{\sigma_x}{\sigma_y} \lesssim 10$
Wiggler parameter	
total lengths	$L_w \approx 100$ m
lengths of wiggler period	$\lambda_w = 0.30$ m
magnetic field	$B = \hat{B}\cos(2\pi s/\lambda_w)$
	$\hat{B} = 0.304$ Tesla
gradient of field ($g = B_x/\ y$)	$g = \hat{g}\cos(2\pi s/\lambda_w)$
	$\hat{g} = 71$ Tesla/m
dispersion function	
deflecting plane	$\eta_y \approx .004$ m
nondeflecting plane	$\eta_x \approx 0$
betatron phase advance	
along the whole wiggler	$\psi_x = 2\pi \cdot 11$
magnet	$\psi_y = 2\pi \cdot 11$

beam lifetime	$\tau > 1$ hour
total beam current	$I \approx 1$ amp
number of bunches	$N_B = 12$

As in all storage rings we assume the particle distribution to be gaussian in energy as well as in the transverse dimensions. The beam emittance therefore is defined for one standard deviation $\varepsilon = \sigma^2/\beta$ with β the betatron function and σ the standard beam size (horizontal σ_x or vertical σ_y). The total energy acceptance of $\pm$ 2.5% then implies a maximum standard energy spread of $\sigma_e/E = 0.4\%$. Here we have used the observation that the total acceptance should be 6 to 7 standard deviations in order to retain a long beam lifetime due to quantum effects of the synchrotron radiation.

II. BASIC STORAGE RING DESIGN

For the basic shape of the storage ring we assume an oval ring with two 180° arcs separated by two long ($\approx$ 100 m) straight sections. One of these straight sections will be used for the wiggler magnet while the other straight section provides ample space for the radio frequency cavity, the beam injection components, skew quadrupoles, and some beam diagnostics equipment.

Beam emittances and damping times are mainly determined by the magnetic lattice parameters of the arc section. From storage ring theory[1] we know the horizontal beam emittance to be determined by

$$\varepsilon \text{ (rad m)} = 3.84 \cdot 10^{-13} \gamma^2 \frac{\langle \mathcal{H} \rangle}{\rho F_c} \quad . \qquad (1)$$

Here $\gamma = E/mc^2$, ρ the bending radius in the arcs, F_c the filling factor for bending magnets in the arc and $\langle\mathcal{H}\rangle = \langle[\eta_x{}^2 + (\beta_x\eta_x{}' - \frac{1}{2}\beta_x{}'\eta_x)^2]/\beta_x\rangle$. The average $\langle\ \rangle$ is taken along the beam line around the whole ring, β_x is the horizontal betatron function and η_x the horizontal dispersion function. Primes ' are derivatives with respect to s along the beam line.

To evaluate the beam emittance we assume a simple FODO-cell lattice. This is a string of quadrupoles with alternating gradients and bending magnets inbetween (see insert in Fig. 1). Scaling laws have been established for such FODO-cells.[2] Since we are interested in a very small beam emittance we choose a strong focussing with 52° degrees of betatron phase advance between quadrupoles which gives $\langle\mathcal{H}\rangle = 1.8\cdot\rho\theta^3$ with θ the bending angle of one bending magnet.[3]

From the required damping time we get immediately the bending radius of the bending magnets. We have[1]

$$n_e = \frac{\tau_e}{T_{rev}} = \frac{E}{U} = \frac{\rho(m)}{8.85\cdot10^{-5}\ E^3(\mathrm{GeV}^3)} \qquad (2)$$

where τ_e is the damping time for synchrotron oscillations, T_{rev} the revolution time and U the energy loss per turn due to synchrotron radiation. We assume here $n_e = 4.7\cdot10^4$ turns. This is more than the required damping time since we neglect here the damping effect of the wiggler magnet. From Eq. (2) we get

$$\rho = 4.318\ \mathrm{m}\ . \qquad (3)$$

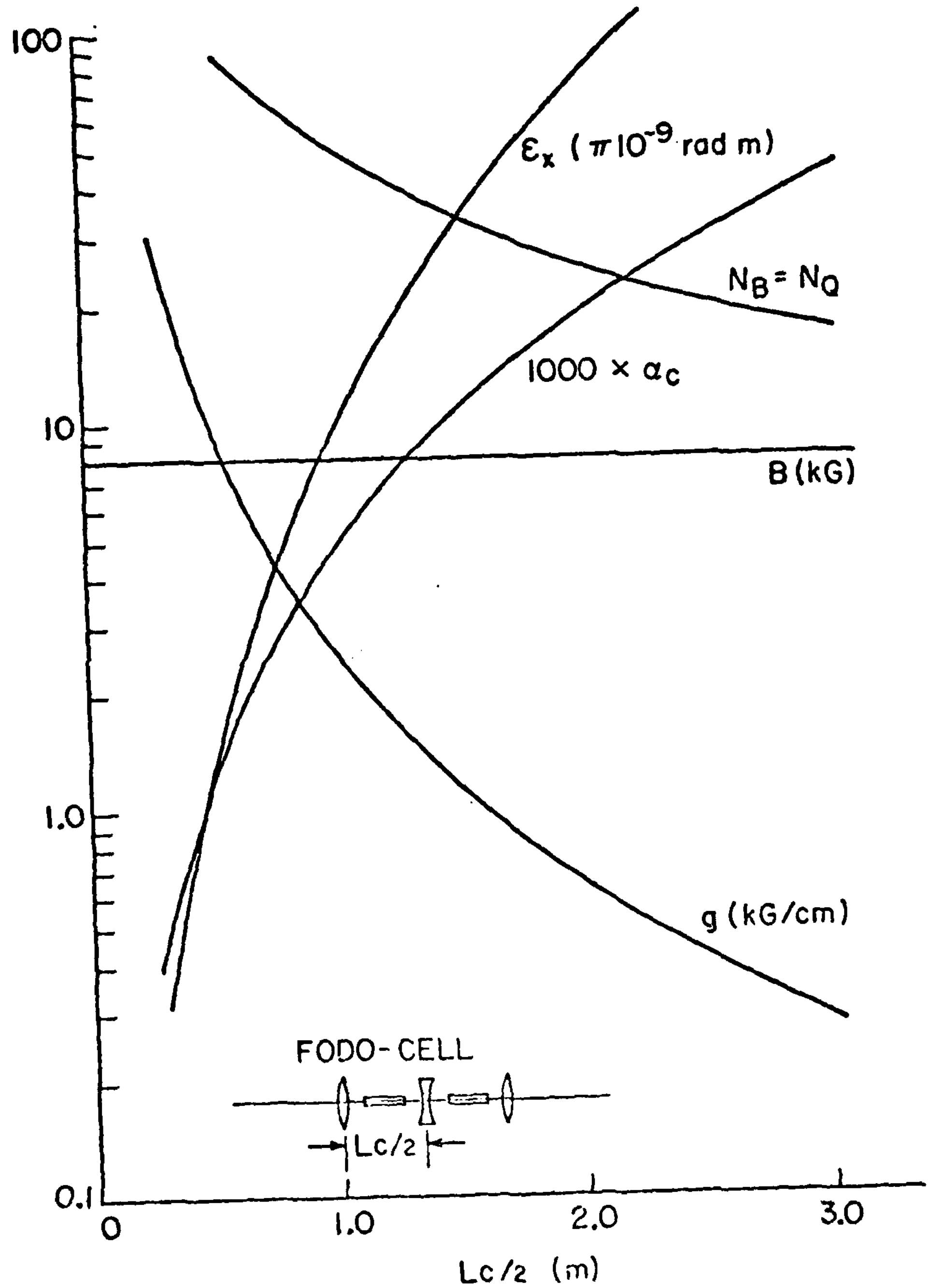

Figure 1. Scaling of Fodo-cell parameters.

We are now ready to calculate some lattice and beam parameters as a function of the distance between the centers of the quadrupoles ($L_{C/2}$). In Fig. 1 the bending field B, the quadrupole gradient g, the number of bending magnets N_B and quadrupoles N_Q, the horizontal beam emittance ε_x and the momentum compaction factor α_c are plotted versus the distance between quadrupoles. The momentum compaction factor is defined as $\alpha_C = (\Delta C/C)/(\Delta E/E)$ where C is the circumference of the storage ring here assumed to be 258 m. For practical reasons, we assume the filling factor for bending magnets to be $F_c = 0.5$ and the lengths of the quadrupoles to be 20% of the distance between the centers of the quadrupoles.

In order to achieve the required small emittance of $2 \cdot 10^{-9}$ rad m for the deflecting plane in the wiggler we find from Fig. 1 that the quadrupole gradient (~ 80 T/m) as well as the number of magnets (≈ 90) has to be very large. It was decided therefore to deflect the electron beam in the wiggler magnet not in the horizontal plane but in the vertical plane. In a plane storage ring with bending magnets only in the horizontal plane we have no vertical dispersion function and therefore the vertical beam emittance according to Eq. (1) is zero. In a real storage ring, however, the vertical beam emittance is finite and determined by coupling of horizontal oscillations into the vertical plane due to rotational misalignment of the quadrupoles. In a well aligned storage ring we can expect to have a vertical beam emittance as small as

$$\varepsilon_y \approx 0.01\varepsilon_x \quad . \tag{4}$$

Since the coupling can easily be increased with the use of skew quadrupoles — quadrupoles that are rotated by 45° — we can easily achieve the required beam emittance in the vertical plane. From Fig. 1, we find now that we could go to large values of $L_{C/2}$ and still get a small vertical emittance by appropriately adjusting the coupling. There is, however, another consideration which forbids us to go to too large distances between quadrupoles. When we calculate the parameters of the rf-system we find that the required rf-voltage and rf-power in a storage ring increases with the momentum compaction factor α_c.[1] Since this factor increases very fast with $L_{C/2}$ (Fig. 1), we will choose a value for $L_{C/2}$ = 1 m for this design study.

III. WIGGLER MAGNET

For the calculation of the energy transfer to the laser, a sinusoidal field and gradient distribution was assumed along the beam line. For the design of the storage ring this sinusoidal field was approximated by a step function to reduce computing time. The difference is insignificant for this feasibility study. We are looking for solutions to the equations of motions which are periodic for the equilibrium orbit of all particles. This means the closed orbit y_0 as well as the dispersion function η_y has to be periodic.

The equations of motion are given by:[4]

$$y_0'' - ky_0 = \frac{1}{\rho}$$

$$\eta_y'' = k\eta = -\frac{1}{\rho} - ky_o \tag{5}$$

where k and $1/\rho$ are the quadrupole strength defined by $k(m^{-2}) = \frac{0.3}{E(GeV)} \cdot g(T/m)$ and $1/\rho$ the curvature. Both quantities are functions of s. Equations (5) can be solved analytically for our field being described by a step function. The result, however, gets complicated for a series of magnets and we decide to use a computer program to find a solution. The curvature $1/\rho$ in a gradient magnet can be expressed by $1/\rho = -k\bar{y}$ if we consider the magnet to be just a quadrupole displaced by $\bar{y}$. If we measure now the transverse amplitude y from the center of the quadrupoles we have $y_0 = y - \bar{y}$ and get from Eqs. (5) for the periodic solution $y \equiv 0$. This is obviously the trivial solution where the beam goes through the field free center of the quadrupoles. To get a periodic solution off center we have to use different bending radii in successive magnets. But in order also to get a periodic nontrivial solution for η we also have to make the field gradient in every other magnet different. It turns out that the differences in the bending field and field gradient are very small (less than 1%) and the average values can be easily adjusted to agree with the specified values. The effect of the difference in the absolute field gradient can be realized either by

different shapes of the magnet pole or by small differences in the magnet lengths. The difference in the bending can be achieved by a transverse displacement of every second magnet with respect to the other magnets. In our example the relative displacement is very small ($\approx$ .3 mm). For this feasibility study we use the following periodic wiggler lattice composed of displaced quadrupoles. The orbit displacement is shown at the end of the element.

element	lengths (m)	displacement (mm)	gradient (T/m)	orbit (mm)
BWP	.057	-4.2680	57.62	-.12
Drift	.036			-.27
BWN	.144	-4.5773	-57.60	-.27
Drift	.036			-.12
BWP	.057	-4.2680	57.62	0

The electron beam in this wiggler magnet makes vertical wiggles with an amplitude of about $\pm$ .14 mm.

The wiggler magnet causes antidamping in the vertical plane due to the simultaneous presence of a field gradient and a dipole field. From storage ring theory we get for the damping times:

$$\tau_x = r(1-\theta_x)$$

$$\tau_y = r(1-\theta_y)$$

$$\tau_e = r(2+\theta_x+\theta_y) \qquad \text{with } r = U \cdot T_{rev}/(2 \cdot E) \quad . \qquad (6)$$

For rectangular bending magnets we get for θ:

$$\theta_x = 2\oint \eta_x k/\rho_x \, ds / \oint (1/\rho_x^2 + 1/\rho_y^2) ds$$

$$\theta_y = -2\oint \eta_x k/\rho_y \, ds / \oint (1/\rho_y^2 + 1/\rho_y^2) ds \qquad (7)$$

The integrals are taken around the whole ring. Note that we have neglected these quantities in Eq. (2). Since $k/\rho_x \equiv 0$ everywhere we have $\theta_x \equiv 0$. For our design storage ring we get in the vertical plane $\theta_y = 0.39$. Although this value is not small we still have sufficient damping in the vertical plane and additional damping for synchrotron oscillations. Therefore we do not need any means in the storage ring to counteract this antidamping. Due to the reduced damping in the vertical plane the vertical emittance is increased. However, only that part of the vertical emittance is increased that comes from quantum fluctuations in the wiggler magnet (the only place in the ring where $\eta_y \neq 0$). A calculation of the vertical emittance including this antidamping effect reveals that the effective vertical emittance is still greatly dominated by coupling and not by quantum fluctuations.

The insertion of the wiggler magnet into the storage ring lattice, therefore, can be done without creating unwanted effects on the beam parameters and beam lifetime.

IV. COMPLETE STORAGE RING LAYOUT

With the arcs and the wiggler magnet specified we use existing[9] computer programs to match the beam envelope of the arc to those in the wiggler magnet. In this matching section we also insert two vertical bending magnets on either side of the wiggler magnet to create the vertical η-function as specified. Both vertical bending magnets are equal in strengths, but of opposite polarity. The center

of the beam in the wiggler, therefore, is parallel to the plane of the storage ring but vertically displaced by an amount equal to the desired η-function. In our example the displacement is 4.2 mm upwards or downwards depending on the polarities of the vertical bending magnets. Either case is equally feasible.

In the other long straight section we do not need these vertical bending magnets and therefore the beam is merely matched into a series of alternating quadrupoles separated by 10 m driftspaces.

When the matching is done, care has to be taken to avoid betatron resonances, e.g., the betatron tunes should be about (m ± 1/4) where m is an integer. We also take care to match the horizontal η-function to zero value in the wiggler magnet as well as in the other straight section. It is very important to avoid a finite η-function where the rf-cavity is placed. A finite η-function there can cause strong synchro-betatron resonances which very likely will be the phenomenon limiting the maximum current in the storage ring.

Figure 2 shows the schematic layout of the storage ring. Figures 3a and 3b show the betatron functions and the η-functions for the same sections. Only the square roots of the betatron function is shown since the beam size is proportional to this quantity. In Table 1 the parameters of all bending magnets and quadrupoles are compiled and Table 2 lists some of the most significant storage ring parameters.

From Table 2 we find the damping time for synchrotron oscillations to be $3 \cdot 10^4$ turns well within specification. The vertical emittance can be chosen anywhere between $5.7 \cdot 10^{-11}$ rad m and $2.85 \cdot 10^{-9}$ rad m

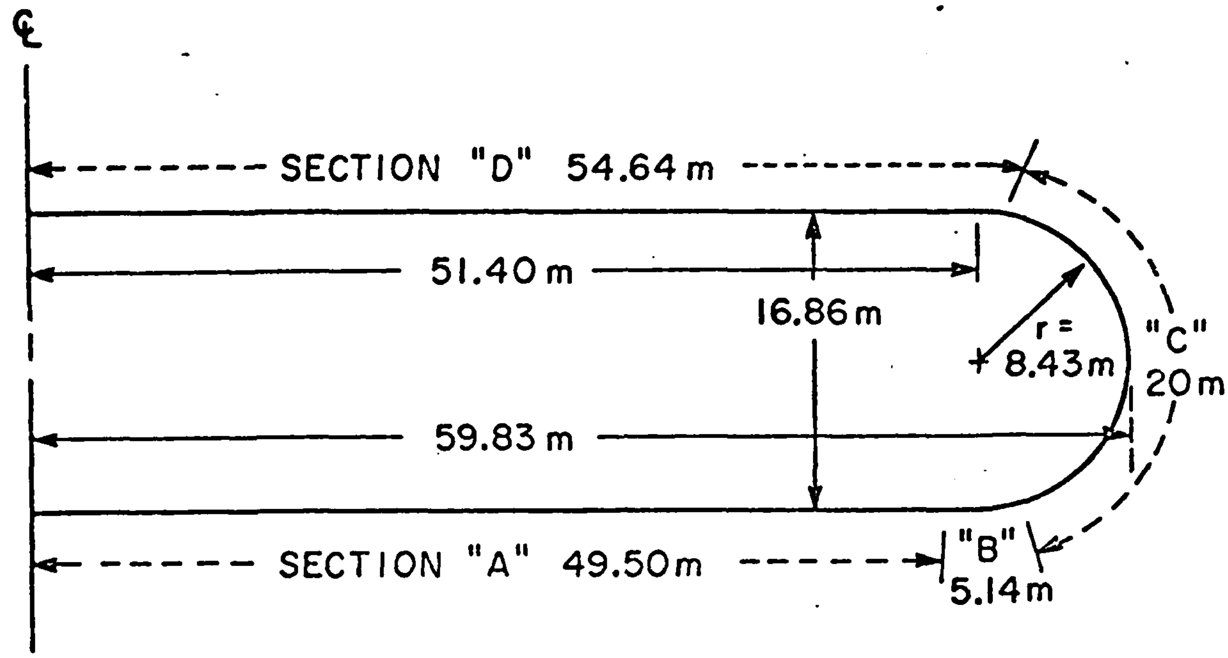

Figure 2. Schematic ring layout.

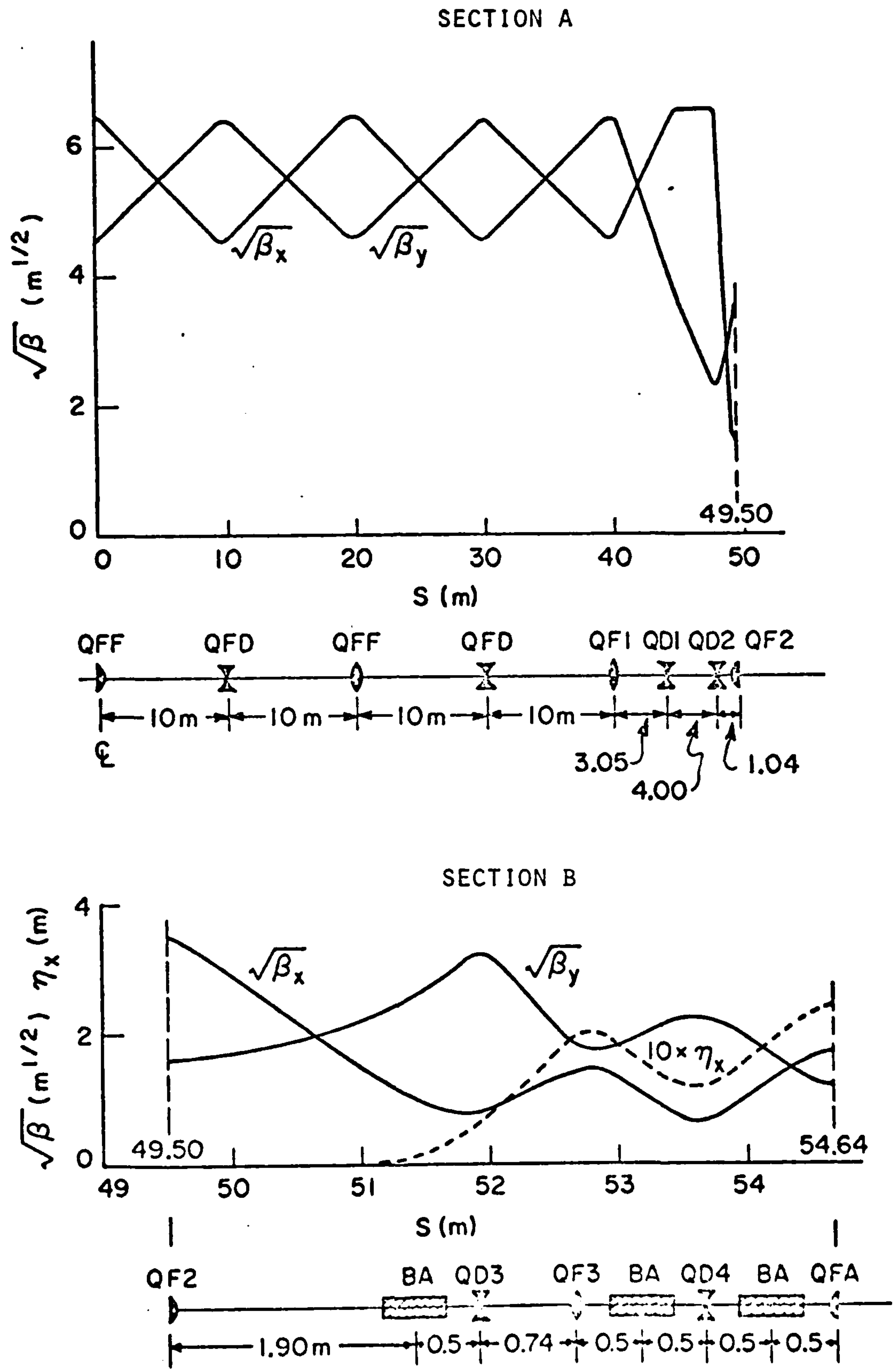

Figure 5a. Lattice functions in Sections A and B.

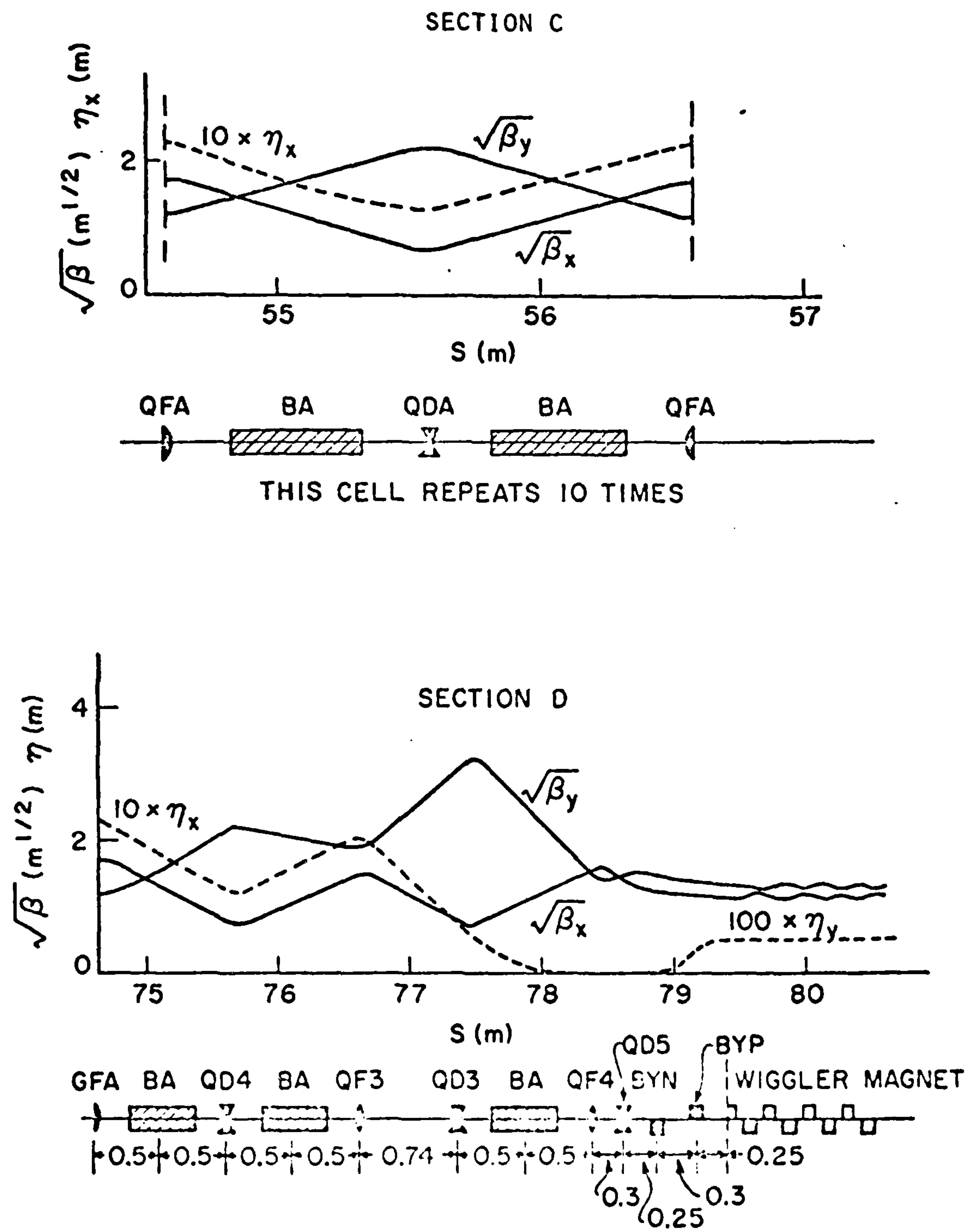

Figure 3b. Lattice Functions in Sections C and D.

Table 1

Magnet Parameters

Magnet	length (m)	field (Tesla)	gradient (Tesla/m)	# of magnets	comment
ring quadrupoles					
QFF	0.20	-	-1.181	3	
QFD	0.20	-	1.181	4	
QF1	0.20	-	-2.430	2	
QD1	0.20	-	-1.088	2	
QD2	0.20	-	8.837	2	
QF2	0.20	-	-11.514	2	
QD3	0.20	-	23.454	4	
QF3	0.20	-	-30.298	4	
QD4	0.20	-	14.358	4	
QFA	0.20	-	-27.019	22	
QDA	0.20	-	18.179	20	
QF4	0.20	-	-26.225	2	
QD5	0.20	-	7.746	2	
ring bending magnets					
BYN	0.10	-0.468	-	2	vertical
BYP	0.10	0.468	-	2	vertical
BA	0.50	0.806	-	52	horizontal
wiggler magnet					
QDH	0.057	.246	57.614	2	half quadrupoles
QDW	0.114	.246	57.614	331	vertically
QFW	0.114	.264	-57.597	332	displaced

Table 2

Storage Ring Parameter

Energy		$E = 1$ GeV
Circumference		$C = 258.56$ m
Working Points		$\nu_x = 20.2291$
		$\nu_y = 15.7643$
Beam Emittance		$\varepsilon_x = 5.7 \cdot 10^{-9}$ rad m
		$\varepsilon_y = 5.7 \cdot 10^{-11}$ rad m
Damping Numbers		$\zeta_x = 1.00$
		$\zeta_y = 0.58$
		$\zeta_e = 2.42$
Damping Times	$n_x = 7.4\ 10^4$	$\tau_x = 63.5$ msec
	$n_y = 12.5\ 10^4$	$\tau_y = 108.8$ msec
	$n_e = 3.0\ 10^4$	$\tau_e = 26.3$ msec
Energy Spread (no laser on)		$\sigma_e/E = 3.5\ 10^{-4}$
Energy Loss per Turn		$U = 27.2$ keV
Momentum Compaction Factor		$\alpha_c = 3.575\ 10^{-3}$
Chromaticity (uncorrected)		$\xi_x = -22.30$
		$\xi_y = -23.29$

depending on the coupling. In a refinement of this design it is easily possible to center that emittance range differently around the required emittance of $2 \cdot 10^{-9}$ rad m.

V. CHROMATICITY AND ENERGY ACCEPTANCE

The focussing in a storage ring as in any focussing system depends on the energy of the particles. Particles with the wrong energy will be focussed differently and we may have stability problems with these particles. The first order chromatic error that needs to be corrected is the so-called chromaticity defined as the ratio of the tune change with energy deviation. The tune is a very characteristic quantity of a storage ring and must be chosen carefully in order to avoid resonances. It is defined as the number of betatron oscillations of a particle per turn. Since both horizontal and vertical betatron oscillations are in general independent there are two tunes for every storage ring. The tunes have to be set such as to avoid resonance conditions given by:[4]

$$n\nu_x - m\nu_y = p$$

where n, m, and p are integers. Not all resonances in electron storage rings are dangerous, however, the strongest being those with small values for (n,m,p). It is clear even if we have chosen safe tunes that a finite chromaticity can move off momentum particles

onto a resonance and cause the loss of the beam. For this reason and to avoid the so-called head tail instability[7] we have to correct the chromaticity. To this goal we use sextupoles around the lattice at places where the dispersion is nonzero. In Fig. 4 the tunes as a function of energy with proper chromaticity connection[6] is shown. The remaining tune variations are small enough not to be worrysome anymore.

Not only the chromaticities have to be corrected, though. The betatron function and the η-functions are momentum dependent too. In addition the sextupoles are nonlinear magnetic elements which have undesirable side effects. We therefore will employ a more sophisticated correction scheme for large energy errors.[6] Since sextupoles are nonlinear elements there are no analytical methods to determine the optimum sextupole distribution as it is possible with the linear quadrupole lattice. A combination of analytical calculations and trial and error choices for the strength and location of the sextupoles is employed to find a stable solution for beam dynamics. This solution is then tested with a tracking program[6] to test the stability of particles with varying amplitudes and energy errors. We have followed this procedure and have determined an energy acceptance of the storage ring described of up to ± 3.5% well in excess of the ± 2.5% required. Particles have been tracked and found stable within amplitudes of:

$$N_x^2 + N_y^2 + N_e^2 \geqslant [illegible]^2$$

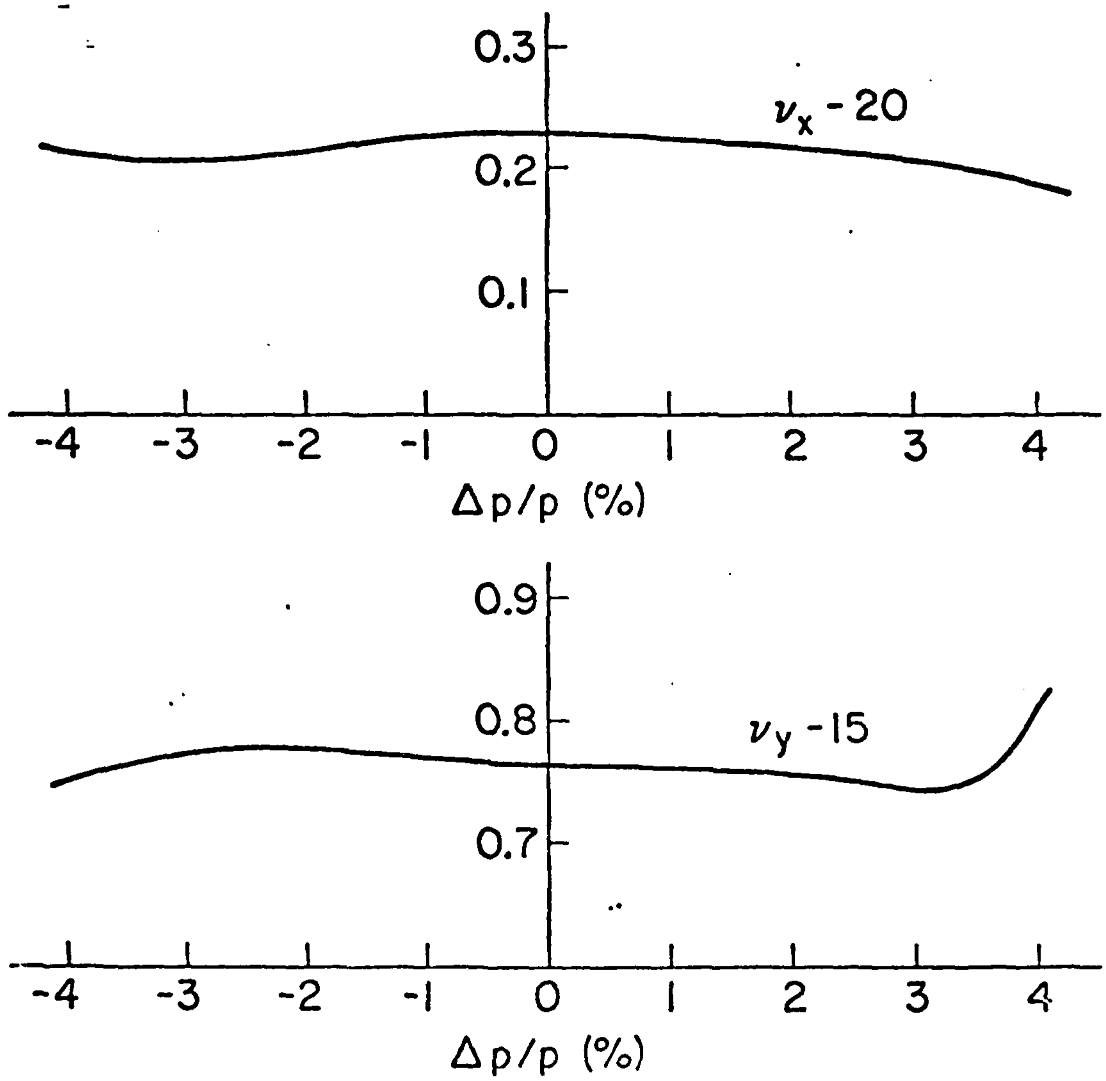

Figure 4. Tune variation with energy.

Table 3

Chromatic Effects

wiggler magnet	$\Delta E/E = -2.5\%$	$\Delta E/E = -1\%$	$\Delta E/E = 0$	$\Delta E/E = +1\%$	$\Delta E/E = +2.5\%$
$\hat{\beta}_x$ (m)	1.49	1.51	1.50	1.46	2.00
$\hat{\beta}_y$ (m)	2.61	1.40	1.50	1.46	2.20
$\hat{\eta}_x$ (m)	.068	.026	0.0	.01	-.004
$\hat{\eta}_y$ (m)	.00482	.00427	.00421	.00424	.00427
phase for total wiggler magnet					
$\Delta\psi_x/2\pi$	11.29	11.11	11.00	10.89	10.77
$\Delta\psi_y/2\pi$	11.40	11.14	11.00	10.88	10.67
arc section					
$\hat{\beta}_x$ (m)	3.16	2.83	3.00	3.05	3.38
$\hat{\beta}_y$ (m)	7.96	5.87	4.57	4.00	5.55
$\hat{\eta}_x$ (m)	.304	.273	.234	.225	.205
$\hat{\eta}_y$ (m)	-.0010	10^{-4}	0.0	$< 10^{-4}$	$< 10^{-4}$
tune of storage ring					
ν_x	20.211	20.227	20.229	20.222	20.215
ν_y	15.781	15.771	15.764	15.761	15.748

where the N's are the amplitudes in units of standard deviations. For the energy deviation a standard value of $(\sigma_e/E)_{max} = 0.4\%$ was taken. We assume a gaussian density distribution and an aperture of at least 7 standard deviations for a beam lifetime due to quantum effects in excess of 50 hours.

With any sextupole correction scheme, however, it is not possible to make the betatron and η-functions totally independent of the energy. All that can be achieved is to minimize the variation of these functions within the considered energy range. Small variations of these functions with energy can be safely tolerated. In Table 3 we show the values of these functions at selected points around the ring for $\Delta E/E = \pm 1\%$ and $\pm 2.5\%$. We see that the variations are small and especially the vertical η-function in the wiggler which is critical to the performance of the laser does not change by more than ± 0.7% in the case of $\Delta E/E = \pm 1\%$ which encloses more than 90% of the beam.

VI. ACCELERATION SYSTEM

The electrons during their revolutions in the storage ring lose energy in the form of so-called synchrotron radiation and to the laser. This energy loss has to be replenished in an acceleration system. In a storage ring this is done by an externally driven rf-cavity phased such that the electrons get an accelerating kick whenever they arrived at the cavity. In order for this to work,

the rf-frequency has to be chosen as an integer multiple of the revolution frequency. The ratio of the rf-frequency to the revolution frequency is called the harmonic number which is equal to the maximum number of bunches that can be stored in the storage ring.

The choice of the rf-frequency has a great impact on the performance and economy of a storage ring in the following way. The rf-voltage not only provides the acceleration needed to compensate the energy loss of the electrons but also creates a potential well in which the electrons can perform stable longitudinal phase oscillations.[1] This potential well has to be deep enough to provide sufficient stability for particles with large energy deviation.

We calculate the required rf-voltage for a maximum energy deviation of 2.5% at different rf-frequencies.

f_{rf} (MHz)	55.65	111.3	222.6
k	48	96	192
V_{rf} (kV)	209	379	716
P_{cy} (kW)	21.8	4.3	10.7
L_{cy} (m)	one cavity	3	3

Here k is the harmonic number, V_{rf} the peak rf-voltage, P_{cy} the thermal losses in the cavity (assumed to be made of copper) and L_{cy} the cavity length. In the case of f_{rf} = 55.7 MHz we have a capacitively loaded cavity, while for the other frequencies we can use resonant cavities. It is clear that the lowest frequency where a resonant cavity is still feasible is economically the best choice since only 4.3 kW are lost in thermal heating of the cavity.

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However, there are also other considerations which have to be looked upon before a frequency can be chosen. The rf-frequency determines the equilibrium bunch length. We want the bunch length to be large to reduce the longitudinal charge density which in turn increases beam lifetime (Touschek Effect)[8] and the interaction with the vacuum chamber.[9] The latter effect causes so-called synchro-betatron resonances which are more pronounced the shorter the bunch length. This is because a short bunch can excite discontinuities in the vacuum chamber to resonate electromagnetically in more modes than longer bunches. In the next table the synchrotron tune ν_s, the bunch length σ_ℓ, and the onset of the turbulent bunch lengthening[9] σ_{th} is shown for different frequencies. Here the turbulent bunch lengthening is the consequence of the bunch interacting with the vacuum chamber. Apart from lengthening the bunch this effect also increases the energy spread which we want to avoid.

f_{rf} (MHz)	55.75	111.3	222.6
ν_s	.0024	.0045	.0088
σ_ℓ (mm)	247	130	67
σ_{th} (mm)	263	99	36

We see that for all frequencies the turbulent bunch lengthening can be just avoided within the accuracy of an empirical formula used. For this formula we assumed that the impedance per unit length of the vacuum chamber would be smaller by a factor of 20 as compared to SPEAR[9] which seems to be technically possible by avoiding discontinuities in the vacuum chamber as much as possible. The synchrotron tune is significant

since it tells us where we will encounter synchro-betatron resonances. These resonances are at tunes given by

$$\nu_{res} = n \pm m \cdot \nu_s$$

where n is the integer closest to the betatron tunes (ν_x or ν_y) and m is an integer up to about $m \approx 10$ to 15. Higher order resonances seem to be not dangerous any more. We would like to work with betatron tunes in the range of about .10 to .30 above the integer value. We see from the table that we do not expect any problems due to synchro-betatron resonances for 55 and 111 MHz. For 222 MHz, however, the synchrotron tune is large and should be avoided.

For further calculations in this report we assume a radio frequency of

$$f_{rf} = 111.3 \text{ MHz} \quad .$$

At this frequency we have a bunch length of $\sigma_\ell = 130$ mm when the laser is on. For a total current of 1 amp in 12 bunches this translates into a peak current per bunch of

$$\hat{I} \approx 85 \text{ amp} \quad .$$

This is well below maximum achieved peak currents in other storage rings.

VII. INJECTION

The accumulation of the electrons in the storage ring is done in the well established way all existing storage rings are filled. Since no source can deliver the necessary beam intensity to fill the storage ring in one shot an accumulation procedure is employed to reach high beam intensities.

In principle, a beam from an injector is launched off center into the storage ring. The injected beam then performs transverse, damped betatron oscillations as it circulates in the storage ring. After one damping time the previously injected beam has damped down to the equilibrium orbit. Now the next pulse can be injected till the desired beam intensity is reached.

Of great importance for the performance of the storage ring is the selection of the injection energy. Wherever large beam intensities are important — as in this design — the injection energy is chosen to be equal to the operation energy. This is due to the fact that all instabilities originating from the charge of the beam itself have the greater effect the lower the beam energy. Therefore if, for example, it is possible to store a beam of 1 amp at 1 GeV instabilities may limit this current to much smaller values at lower energies. It is clear that the injection energy will determine the maximum current that can be stored (assuming the injection energy is not higher than the operating energy).

As for the synchrotron light facilities presently under construction,[10] we assume to have a fast cycling 1 GeV booster synchrotron

injector filled by a linear S-band accelerator of about 100 MeV. The beam intensity that can be routinely obtained at 100 MeV are about 10^9 electrons in a pulse of 1 nsec or 3 S-band buckets and an emittance of $\varepsilon = 3 \cdot 10^{-6}$ rad m. Due to adiabatic damping during acceleration, this emittance is reduced to

$$\varepsilon_I = 3 \cdot 10^{-7} \text{ rad m}$$

$$\text{at } E_I = 1 \text{ GeV} \quad .$$

This emittance is smaller than the acceptance of the storage ring, which is limited by the aperture of the wiggler magnet. If we assume an aperture of ± 3.2 mm the acceptance is $6.8 \cdot 10^{-7}$ rad m. This acceptance is big enough to design an efficient injection process.

We assume the booster synchrotron will cycle at 60 pps. There are twelve bunches to be filled in the storage ring to a current of 85 ma each. This corresponds to $4.6 \cdot 10^{11}$ electrons per bunch. We further assume that all electrons from one pulse of the booster synchrotron are stored in only one of the twelve buckets to be filled in the storage ring. With an intensity of 10^9 electrons per pulse we calculate an accumulation time of 91 sec. Since a real system does not always work at its peak performance it is prudent to assume not more than about 20% average injection efficiency for various reasons. With this assumption, we get a filling time of the storage ring required to get an average circulating beam of

1 ampere of

$$T_I \lesssim 7.5 \text{ min} .$$

VIII. BEAM CROSS SECTION AND APERTURE

We have two distinct regimes of operation for which we have to determine the beam dimensions. In both cases we assume that we have set the coupling at K = 82% which gives the following beam emittances due to quantum effects of the synchrotron radiation.

$$\varepsilon_x = 3.6 \cdot 10^{-9} \text{ rad m}$$

$$\varepsilon_y = 2.0 \cdot 10^{-9} \text{ rad m} .$$

It is assumed that the laser operation does not affect the beam emittance. We have to avoid setting a too small coupling at any time of the operation. This would unnecessarily increase the particle density with a consequent reduction of the beam lifetime due to Touschek effect.

The two regimes of operations are now the situations where the laser is off or on. As long as the laser is off we have a natural energy spread in the beam determined only by the synchrotron radiation and damping:

$$(\sigma_e/E)_{nat} = 3.5 \cdot 10^{-4} .$$

When the laser is on and the whole system performs at the design parameters we expect the energy spread to be increased to

$$(\sigma_e/E)_L = 4 \cdot 10^{-3} \quad .$$

Because of the finite η-function around the ring this increase in energy spread by more than a factor of 10 has a strong impact on the beam size.

The beam sizes for both regimes of operation are shown in Figs. 5a and 5b, with (σ_x, σ_y) the natural beam sizes and σ_{xL} the horizontal beam size with the laser on. The vertical beam size is changed only insignificantly when the laser is turned on.

From Figs. 5a, 5b, we can draw the following conclusions for the aperture required for the beam in the magnets. The actual magnet apertures have to be somewhat larger to accommodate the vacuum chamber. We assume a required beam aperture of ± 15 σ plus an allowance of ± 5 mm for orbit distortions. This results in an aperture requirement for all quadrupoles of $\pm (15\sigma_x + 5) = \pm 20$ mm in the horizontal plane and $\pm (15\sigma_y + 5) = \pm 10$ mm in the vertical plane. The actual beam cross section can be described by an ellipse with half axes of 10 and 20 mm.

In the bending magnets we have to add to the horizontal beam size the sagitta of the central orbit since we assume the bending magnets for economic reasons to be straight rectangular magnets. We get for the beam aperture in the bending magnets including sagitta

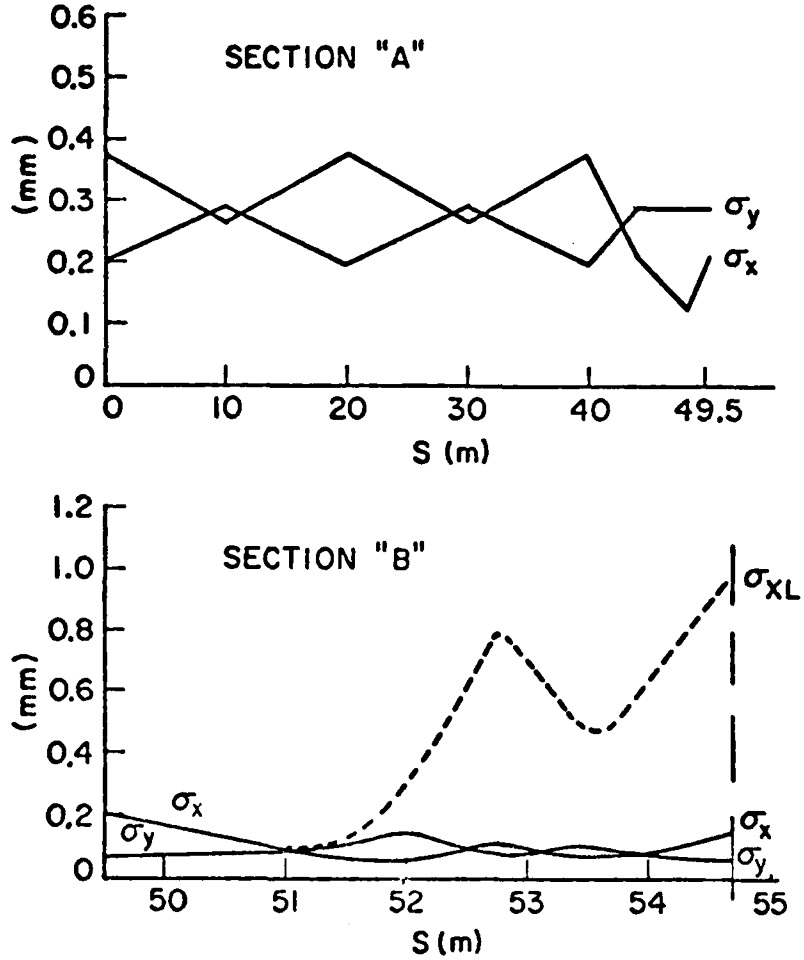

Figure 5a. Beam size in Sections A and B.

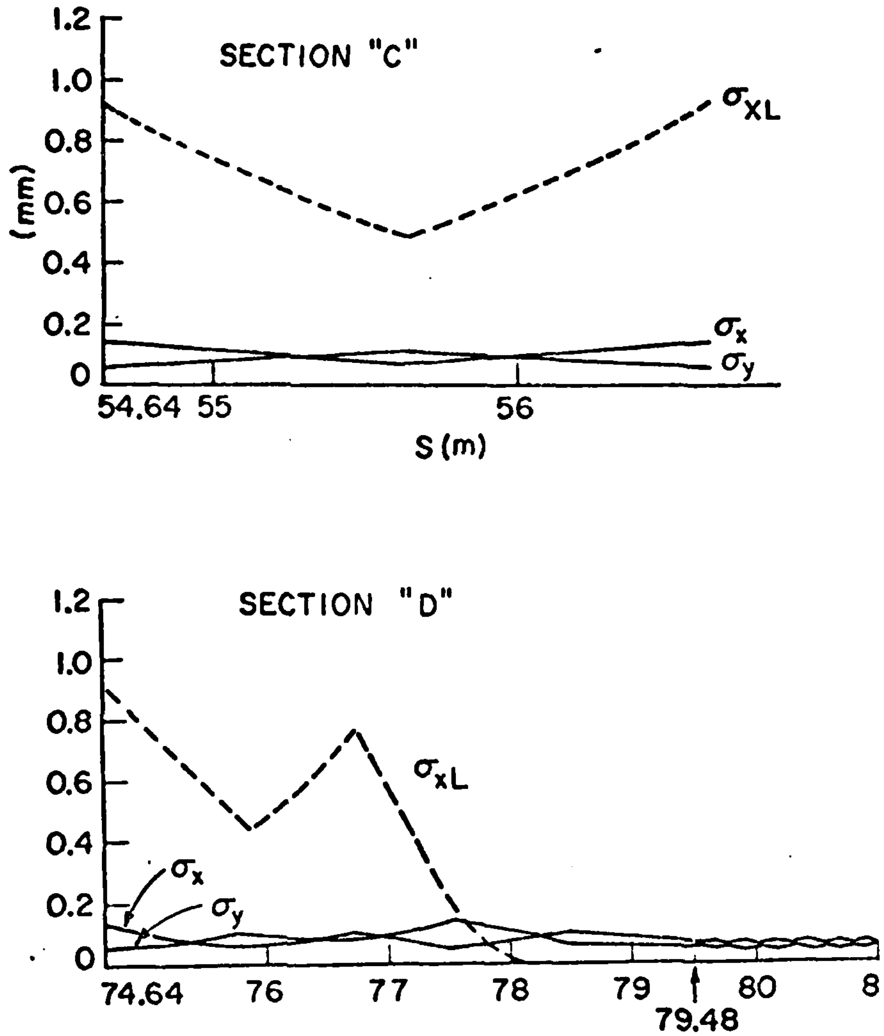

Figure 5b. Beam size in Sections C and D.

$\pm$ 24 mm in the horizontal plane and $\pm$ 10 mm in the vertical plane. In the wiggler magnet we have much smaller beam sizes and the required beam aperture is only

$$\pm 15\, \sigma_{x,y} = \pm 1.2 \text{ mm} \quad .$$

Because of the large gradient we cannot allow orbit distortions of $\pm$ 5 mm. The good field region in the wiggler magnets is not large enough. How much space will be available has to be determined from an actual magnet design. We do require, however, that there be an allowance for orbit distortions and injection of at least $\pm$ 2 mm.

In general, the aperture requirements are modest and do not seem to create any technical problems for the design of the magnets.

IX. BEAM LIFETIME

Several parameters affect the beam lifetime in a storage ring. The most important are

1. quantum fluctuations[1]
2. residual gas bremsstrahlung
3. Touschek effect.[8]

Since the energy loss into synchrotron radiation has a wide spectrum, occasionally it is possible for a particle to emit a high energy photon which causes a large perturbation of the betatron and synchrotron oscillation. Calculations of this effect[1] show that the beam lifetime due to this process is in excess of 50 hours if the aperture

of the vacuum chamber is larger than about $\pm 6\frac{1}{2}\sigma_x$ and $\pm 6\frac{1}{2}\sigma_y$. We have chosen the aperture to be $\pm$ 15 σ to be prepared for some unforeseen beam blow up and unavoidable closed orbit distortions.

The "aperture" in the longitudinal phase space is determined by the rf-system. In the section on the acceleration system we already have determined the rf-voltage to be sufficiently large in order to obtain a lifetime of at least 50 hours due to quantum effects for all particles within an energy spread of ± 2.5%.

Particles also can be lost due to scattering on nuclei of the residual gas. The lifetime due to this effect can be calculated and gives in our case

$$\tau_{gr}(h) = \frac{114}{p(\text{ntorr})}$$

where p is the residual gas pressure in n torr. To get a beam lifetime of about 10 hours the vacuum pressure has to be better than 10^{-8} torr in the presence of synchrotron radiation. Experience shows that this can be accomplished in a well cleaned and baked vacuum system. Pumps will be required all around the storage ring. To reduce cost it is customary to use the magnetic field of the bending magnets for distributed pumps which is possible in this storage ring design too.

The most significant effect to limit the beam lifetime in low energy, high intensity storage rings is the so-called Touschek effect. In densely populated bunches two transversely oscillating particles

within the same bunch can collide in such a way that the transverse momenta of the particles are transformed into longitudinal momenta. In this process the energy of one particle is increased and that of the other particle is decreased. If that energy change is too large both particles can fall out of the energy acceptance of the storage ring and be lost. This effect depends very sensitively on the bunch density or the bunch volume which is the reason we were looking for a long bunch length and a large coupling at all times. With the laser off we calculate a Touschek lifetime of[8]

$$T_{To} = 34 \text{ min} .$$

When the laser is turned on the beam size is enlarged due to the larger caused energy spread and the Touschek lifetime is

$$T_{TL} \approx 13 \text{ hours} .$$

This shows that once the laser is working properly we can expect a comfortable beam lifetime in excess of 10 hours.

X. INSTABILITIES

The electron beam in a storage ring being an oscillator is subject to a large variety of external time dependent forces. If any of these driving forces has a frequency equal to one of the betatron or synchrotron frequencies or harmonics thereof, there is a

potential for instability. Some of these driving forces are very weak and the resulting rise time is less than the damping time. In this case no instability will occur. Other instabilities drive the whole bunch to large coherent oscillations. Such instabilities are best controlled by a transverse or longitudinal feedback system. It is certainly advisable for a high current storage ring like this one to provide for both kinds of feedback system.

In a multibunch storage ring each bunch via the impedance of the vacuum chamber can interact with any other bunch and cause an instability. The cure for this kind of instability is a broad band feedback system or an additional rf-system to give each bunch a different synchrotron frequency. For transverse multibunch instabilities an rf-quadrupole can be used. More research is necessary to decide which system is the most effective for this storage ring.

We already mentioned the so-called head tail instability which limits the beam current in existing storage rings to about one milliampere. This instability can be cured by correcting the otherwise negative chromaticities to zero or slightly positive values with the use of sextupoles. We have made provisions for this chromaticity correction.

Interaction of a dense bunch with its environment can cause this bunch to oscillate in quadrupole and higher order modes. This effect has been observed in most of the existing storage rings. The consequence of this instability is a bunch lengthening combined with an increase in the energy spread. From measurements at SPEAR,[9] an

empirical formula was derived which can be used to calculate the onset of this instability. We have chosen parameters for this storage ring such as to just avoid what is generally called turbulent bunch lengthening. However, in case the threshold should be exceeded by not too much in this storage ring, the beam lifetime is not necessarily reduced as evidenced by the performance of SPEAR where turbulent bunchlengthening is present in most of the lower energy operations.

In low energy storage rings the self fields of the beam as well as image fields cause a change in the focussing or a change in the tunes of the beam.[11] Neglecting image fields this tune change in the storage ring described here is only $\delta\nu_0 \approx 0.0014$ and if we take the image fields into account the tune shift is $\delta\nu \approx 0.016$. This is based on a vacuum chamber of about 1 cm radius. The tune shifts are small enough not to be worrysome at all.

Apart from single Coulomb scattering (Touschek Effect) we also have to concern ourselves on the effect of multiple Coulomb scattering with small momentum transfers per collision.[8] The effect is an increase in the energy spread and emittance of the beam. A calculation of this effect for this storage ring shows that the energy spread and emittance is increased due to this effect by less than 0.1%.

The last effect we have to worry about are the so-called synchro-betatron resonances. Bunches with high charge density can excite the surrounding vacuum chamber to act like rf-cavities oscillating

in various modes.[12] Any such mode with the right frequency can excite synchro-betatron resonances. The same effect can be caused when there is a finite η-function in the accelerating cavity. Several "cures" are possible and should be followed. First the vacuum chamber should be built as smooth as possible to avoid any discontinuity. The η-function at the cavity should be made zero. Although we have designed the storage ring to have a zero η-function at the cavity there will be always some value left due to errors in the magnet fields and alignment of the magnets. Special correction fields, however, can be employed to vary the residual η-function at the cavity. During operation these fields would be set such as to minimize beam blow up due to synchro-betatron resonances.

It is also planned to set the tune of the storage ring such as to avoid these resonances.

An additional precaution has been taken to minimize these resonances by choosing a very small synchrotron frequency. For the design tunes then only very high order synchro-betatron resonances can be excited. Those, however, are usually very weak.

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